Temporal and Spatial Characteristics of the Ciliate *Mesodinium rubrum* in the Western Isles Region of the Bay of Fundy

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by

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ABSTRACT

Martin, J.L., Hastey, C.D., LeGresley, M.M., and Page, F.H. 2007. Temporal and spatial characteristics of the ciliate *Mesodinium rubrum* in the Western Isles region of the Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2714: iii + 27 p.

The abundance of the ciliate *Mesodinium rubrum* has been monitored at five locations in the Bay of Fundy, eastern Canada, at weekly to monthly intervals since 1987. *M. rubrum* was present at all stations an average of 94% of the sampling dates from 1987 to 2004. The date for the first appearance of *M. rubrum* in a given year was inter-annually variable and ranged from January to April. Maximum concentrations occurred anywhere between May and October and tended to be earliest at Lime Kiln Bay and the Wolves and latest in the more inshore Passamaquoddy Bay stations and Deadmans Harbour. Brandy Cove, the most inshore station in Passamaquoddy Bay, had the highest concentrations, suggesting that this region was more conducive to the higher cell densities and blooms of *M. rubrum*. The annual maximum concentration varied among stations and between years by up to 5.7 orders of magnitude. The median maximum value (cells•L^{-1}) was 13 740 (Station 3), 12 600 (Station 15), 16 400 (Station 16), 19 460 (Station 17) and 70 296 (Station 25). The annual duration of the presence of *M. rubrum* ranged throughout the year and had a mean of 244 d, whereas the duration of the presence containing the annual maximum concentration varied from 7-365 d. The characteristics of the annual *M. rubrum* blooms vary between years and stations with the number of blooms or high abundance periods varying from one to two per year.

RÉSUMÉ

Martin, J.L., Hastey, C.D., LeGresley, M.M., and Page, F.H. 2007. Temporal and spatial characteristics of the ciliate *Mesodinium rubrum* in the Western Isles region of the Bay of Fundy. Can. Tech. Rep. Fish. Aquat. Sci. 2714: iii + 27 p.

Depuis 1987, l'abondance du cilié *Mesodinium rubrum* a été suivie à 5 sites situés dans la baie de Fundy, dans l'est du Canada soit à chaque semaine ou à chaque mois. De 1987 à 2004, *M. rubrum* était présent en moyenne dans 94% des échantillons et à toutes les stations. La date de la première observation de l'année du *M. rubrum* était variable entre années et s'étalait de janvier à avril. Les concentrations maximales ont eu lieu entre mai et octobre et avaient tendance à se produire plus tôt dans la baie Lime Kiln et aux îles Wolves mais plus tard dans les sites abrités de la baie de Passamaquoddy et du havre de Deadmans. Les stations plus côtières de la baie Passamaquoddy jouissaient des concentrations les plus élevées suggérant que cette région est plus propice aux proliférations de *M. rubrum*. La concentration maximale annuelle variait entre stations et aussi entre années par 5.7 ordres de grandeur. La médiane maximale (cellules •L^{-1}) était 13 740 (Station 3), 12 600 (Station 15), 16 400 (Station 16), 19 460 (Station 17) et 70 296 (Station 25). La moyenne de la durée annuelle de la présence de *M. rubrum* était de 244 jours tandis que la durée de la présence ayant la plus grande concentration variait de 7-365 jours. Les caractéristiques des efflorescences annuelles du *M. rubrum* diffèrent entre années et entre stations et varient d'une à deux proliférations par année.

INTRODUCTION

Although the majority of phytoplankton species occur in the environment without causing adverse effects, there are a few that are known to cause harm. When these harmful algal blooms (HABs) occur in areas where Atlantic salmon (*Salmo salar*) farming is conducted, the health of the caged salmon can be compromised. The salmonid mariculture industry in southwest New Brunswick consists of more than 90 active farms which could potentially be impacted by HABs.

Impacts to cultured organisms and fisheries from HABs have been observed in various regions of the world (White 1980; Anderson et al. 2001; Landsberg 2002; Kim et al. 2004; Doucette et al. 2006), and specifically to cultured salmon in regions such as:

- Atlantic Canada –
  - Bay of Fundy: *Alexandrium fundyense*, and *Mesodinium rubrum* (Martin et al. 2001a, 2006a),
  - Nova Scotia: *Alexandrium tamarense* (Cembella et al. 2002);
- Faroe Islands – *Alexandrium* (formerly *Gonyaulax*) *excavata* (Mortensen 1985);
- Northwest Pacific - *Chaetoceros convolutus*, *Chaetoceros concavicornis* and *Corethron* sp. (Gaines and Taylor 1986; Rensel et al. 1989; Speare and Ferguson 1989; Horner et al. 1990, 1997; Albright et. al.1993; Rensel 1993);
- Europe - *Gyrodinium aureolum* (Dahl and Tangen 1990, 1993; Romdhane et al. 1998),
- Chile - *Leptocylindrus minimus* (Clément and Lembeye 1993).

HABs have been known to affect fish through either of the following methods: neurotoxins, gill irritation/damage (mechanically or through the production of haemolytic substances) or asphyxiation (oxygen depletion). Farmed fish are particularly vulnerable to harmful phytoplankton blooms as they cannot escape or avoid them. The result may be mortality or stress in both smolts and market-size salmon and loss of growth due to a decrease in feeding during a severe bloom event. These effects have caused millions of dollars of lost revenue to the affected salmon farmers, and insurance companies are interested in knowing what farmers are doing to mitigate potential phytoplankton-related losses. In cases where there is an anticipation of a problem, introduction of fall smolts into cages may need to be delayed due to sensitivity to phytoplankton blooms, or harvesting schedules may be adjusted to avoid exposure to a bloom.

Salmon operations in the southwestern New Brunswick region of the Bay of Fundy have been impacted by HABs several times within the past decade. Those farms located within the Passamaquoddy and Bocabec Bay areas have been impacted more so than those elsewhere. Although HABs occur less frequently in regions outside Passamaquoddy Bay, harmful blooms causing severe economic losses occurred at several farms in the Grand Manan Island area in 2003. In 2004, harmful blooms occurred in the region between Lime Kiln Bay and Seeleys Cove, affecting salmon farms in that area as well (Fig. 2).

A phytoplankton monitoring program was initiated in the Western Isles region of the Bay of Fundy in 1987 due to growing concerns that incidents involving HABs seemed to be increasing in intensity, frequency and geographic distribution throughout the world (Anderson 1989; Smayda 1990; Hallegraeff 1993, 1995). Although more than 48 species of dinoflagellates, 94

species of diatoms and 21 other species (including smaller zooplankton and ciliates) have been observed from the sampling program in the southwestern New Brunswick region of the Bay of Fundy, the majority do not cause harm (Wildish et al. 1988, 1990; Martin et al. 1995, 1999, 2001b, 2006b).

The purposes of the phytoplankton study when it was initiated were: to establish baseline data on phytoplankton populations in the lower Bay of Fundy, since little detailed work had been published since studies by Davidson (1934) and Gran and Braarud (1935); to identify harmful algal species that could potentially cause harm to the aquaculture industry; to provide an early warning to the aquaculture industries by sorting and identifying samples soon after collection; and to determine patterns and trends in phytoplankton populations. Another purpose of the study was to determine whether there were environmental changes, such as changing trends in phytoplankton populations as a result of the salmon farming industry. Incidences of fish mortalities, especially those held captive in net pens, had also been increasing in other regions of the world. Some of these increases can be attributed to increased awareness, both in the scientific and public communities, as well as the increased use of inshore coastal waters for aquaculture, tourism and other activities.

It is well known that phytoplankton blooms are notoriously difficult to predict. Scientists in various parts of the world have been working on this for decades with little success to date. Two decades of monitoring phytoplankton within the southwestern New Brunswick area of the Bay of Fundy have indicated that the general seasonal timing of the blooms of some species is quite consistent and hence predictable to this extent. Some initial statistical analyses have indicated that sophisticated time series analysis techniques have potential for forecasting of phytoplankton abundance.

A research project (Chang et al. 2005) was funded under the Department of Fisheries and Oceans (DFO) Aquaculture Collaborative Research Development Program (ACRDP) to study data analysis strategies to provide information concerning:

1) the temporal and spatial scales of variability in the concentration of potentially harmful phytoplankton species;
2) the effectiveness of sampling and data analyses approaches for detecting the presence of potentially harmful phytoplankton species; and
3) the effectiveness of the sampling and data analyses approaches for detecting and projecting a temporal trend in the abundance of a harmful algal species.

This paper is one of a series of manuscripts being written dealing with: determining temporal and spatial characteristics of particular blooms of harmful algae in the southwestern New Brunswick area from existing phytoplankton monitoring data since 1987; evaluating the statistical potential of these time series to give an early indication of a pending HAB; and determining the similarity between time series of phytoplankton collected at individual locations. Although a number of species of phytoplankton were selected from the dataset for analyses, this particular paper focuses on the ciliate *Mesodinium rubrum*. A total of 10 species are being addressed as part of the project and include either species that have been suggested to have caused problems with salmon in the Bay of Fundy, or species observed in the Bay of

Fundy that have been implicated in fish problems elsewhere in the world, such as *Eucampia zodiacus*, *Ditylum brightwellii*, *M. rubrum*, *Chaetoceros socialis*, *C. concavicornis*, *C. convolutus*, *Corethron criophilum*, *L. minimus*, *A. fundyense and Pseudo-nitzschia* spp. Results for *A. fundyense* and *E. zodiacus* have been published previously (Martin et al. 2007; Page et al. 2004, 2005, 2006)

M. rubrum (Fig. 1) is a planktonic marine ciliate that appears to be cosmopolitan and is found in estuarine, lagoonal and coastal systems throughout the world (Lindholm 1985). It has been responsible for causing brick red water conditions in many regions including the Bay of Fundy and Gulf of Maine (Ryther 1967; McAlice 1968; Taylor et al. 1971; White et al. 1977). Cells are extremely fragile, somewhat oval, 25-45 µm in length and 18-34 µm in width, and have a broad band of cilia around their middle. They swim with rapid movements and it has been recorded that they can swim at speeds of 5 000 $\mu m \cdot sec^{-1}$ (Lindholm 1981) making it very difficult to study live under the microscope. *M. rubrum* is actually two organisms that appear to exist in a symbiotic relationship or in association with each other. The two organisms are a ciliate (*M. rubrum*) and a cryptomonad (Barber et al. 1969; Hibberd 1977, Johnson and Stoecker 2005; Hansen and Fenchel 2006). *M. rubrum* Lohmann 1908 (= *Myrionecta rubra* Jankowski 1976) was earlier also referred to as *Cyclotrichium meunieri* (Powers 1932; Taylor et al. 1971).

MATERIALS AND METHODS

Sampling was initiated in 1987 in Lime Kiln Bay (Fig. 2, Station #3 – where a number of aquaculture sites are located) and at the following three stations in 1988: Brandy Cove (Fig. 2 Station #17 – a brackish site influenced by the St. Croix River estuary), Deadmans Harbour (Fig. 2, Station #15 – an open bay with offshore influence), and the Wolves Islands (Fig. 2, Station #16 – an offshore indicator site). An extra sampling site (Fig. 2, Station #25) was added in mid-Passamaquoddy Bay in 1999 following the observation that Brandy Cove was not a good indicator site for cell densities of algal blooms within Passamaquoddy Bay.

Sampling was conducted aboard the research vessel, CCGC *PANDALUS III*. Weekly samples were collected from early May to the end of September or October, depending on the decline of the fall phytoplankton blooms. Biweekly sampling was conducted in the shoulder bloom months such as April and October (when phytoplankton cell densities had begun to increase or decrease) and monthly during all other colder months.

Phytoplankton samples were collected at the surface by bucket from all five stations, at depths of 10, 25, and 50 m with a Niskin bottle at Station 16 and sub-surface samples and 1 m above bottom at selected stations. Water samples (250 mL) were immediately preserved with 5 mL formaldehyde:acetic acid. Later, 50-mL subsamples were settled in counting chambers for 16 h. All phytoplankton greater than 5 µm were identified and enumerated (as $cells \cdot L^{-1}$) with the Utermöhl technique using a Nikon inverted microscope (Sournia 1978).

Following analyses for phytoplankton abundance and distribution, the results were entered into a Microsoft Access database with the following fields: survey type, sampling station, date, organism (species name), code ("1" – dinoflagellate, "2" – diatom and "3" other which included ciliates and smaller zooplankton), and depth (only surface samples were used for this report

although samples were collected at other depths at selected sites). The dataset was used to generate a time-series of the near surface abundance of *M. rubrum* for each of the five primary sampling stations. Data was retrieved from Access using queries for the first occurrence, maximum occurrence, etc., and copied into an Excel spreadsheet for sorting and data manipulation. Three-point running medians and logarithms were calculated using Excel. Data were then imported into SigmaPlot (2001) for plotting. SigmaPlot was used for plotting time series of abundance and bubble plots for each station. Bubble plots were produced using a time-series for each year and converting the concentrations (cells•L^{-1}) to represent the area of the circle (bubble). Lattice plots showing annual first appearance versus year, date of maximum occurrence versus year, length of maximum bloom versus year and maximum concentration versus year were created using "R" (v. 2.4.0): A Programming Environment for Data Analysis and Graphics.

Data from phytoplankton analyses of the total community for 1987- 2000 have been previously published (Wildish et al. 1988, 1990; Martin et al. 1995, 1999, 2001b, 2006b); the data from 2001-04 is not as yet published (J.L. Martin, Biological Station, 531 Brandy Cove Road, St. Andrews, NB E5B 2L9, pers. commun.).

RESULTS

Table 1 shows the number of sample days for each station for each year from 1987-2004. Sample days varied between the stations from 177 d at Station 25 to 513 d at Station 3. Variables, such as the fact that sampling occurred only at Station 3 in 1987 and the first part of 1988, resulted in the higher number of sample days at that particular location. Station 17 was sampled on a regular basis once sampling was initiated due to its easy access and close proximity to the Biological Station. Very occasionally it was not possible to sample Station 15 due to weather or the fact that the harbour was shut off by the herring fishery. Sampling at Station 16 was occasionally affected by weather or sea conditions either unsafe or not conducive for deployment of sampling gear. Sampling at Station 25 was initiated in 1999.

Figures 3, 4, 5, 6 and 7 show cell densities of *M. rubrum* from 1987 to 2004 on both log and linear scales from Lime Kiln Bay (#3), Deadmans Harbour (#15), the Wolves Islands (#16), Brandy Cove (#17), and mid-Passamaquoddy Bay (#25), respectively. *M. rubrum* was present during all years at all stations. The years where the maximum count was greater than the mean of the maximum count for each station were as follows: Station 3 – 2003, 1990, 2000, 2001, 2002, and 2004; Station 15 – 1990, 2002, 1992, 2004, 1994, 2003; Station 16 – 2004, 1993, 1998, 2000, 1988, 1992, 2003, 1989; Station 17 – 1989, 2001; and Station 25 – 2000, 2003. In 1989 when Station 17 had the highest occurrence at 5.61×10^5 cells•L^{-1}, Stations 3, 15 and 16 did not reach 2×10^4. Obviously, the count in 1989 at Station 17 was so high that it forced a high mean such that only 2 yr out of 17 were higher than the mean. The highest concentration for Station 15 was in 1990. In this year, there were large counts at Stations 3 and 17, but not at the Wolves. Similarly, Station 15 had high counts in 1992 while the other stations had low counts. This trend continued, as can be seen in Table 2 where a high count at one station does not imply high counts at other stations. In the later years of the survey, Stations 3 or 15 had high counts when Station 25 did as well.

Table 1. Number of sampling days per station for each year from 1987-2004. No data means that samples were not collected.

Year	Station 3	Station 15	Station 16	Station 17	Station 25
1987	20	n/a	n/a	n/a	n/a
1988	28	23	25	25	n/a
1989	31	30	25	31	n/a
1990	31	28	25	29	n/a
1991	32	32	22	32	n/a
1992	29	29	24	29	n/a
1993	29	29	26	29	n/a
1994	27	27	19	27	n/a
1995	27	27	27	27	n/a
1996	25	24	22	24	n/a
1997	25	26	23	24	n/a
1998	29	28	27	29	n/a
1999	29	28	28	29	26
2000	29	30	31	31	31
2001	30	30	30	31	31
2002	28	25	24	27	26
2003	33	33	30	33	32
2004	31	31	31	31	31
Total	513	480	439	488	177

Table 2 and Fig. 9 show the *M. rubrum* maximum cell densities in cells•L^{-1} observed during each year at each of the 5 stations. Maximum cell densities from the period 1987-2004 did not occur in the same year at any of the same locations. Maximum cell concentrations for the more inshore sheltered sites were observed at Stations 3 (9.59×10^4), 17 (5.61×10^5) and 25 (1.04×10^5) in 2003, 1989, and 2000, respectively. The highest densities for Stations 15 (1.08×10^5) and 16 (3.73×10^4), the more offshore and offshore exposed sites, were observed in 1990 and 2004. Day of year where the maximum cell concentration for a given year at each station was observed is shown in Fig. 10.

Figure 8 shows bubble plots indicating the presence of *M. rubrum* at the five stations since 1987. The size of the circle reflects the number of cells observed – the larger the circle, the larger the bloom or concentration of cells. This figure shows that the largest bubble and corresponding cell concentration (5.61×10^5 cells•L^{-1}) at Station 17 in 1989 was clearly more than 5-fold greater than any other concentration observed during the study period. Unfortunately, Station 25 was not sampled at that time so we are unable to say whether numbers from Station 25 might have been greater than those at Station 17 during the same period. A red tide was observed on September 3, 1998 in Bocabec Bay (upper Passamaquoddy Bay). Although this was not one of the regular sampling stations, a few samples were taken in nearby areas over the next 2 wk. Mid-Passamaquoddy Bay had 1.3×10^4 cells•L^{-1} on September 8, 1998

Table 2. Maximum *M. rubrum* cell densities (in cells•L^{-1}) from 1987-2004 at stations 3, 15, 16, 17 and 25. Shaded numbers indicate maximum cell density for a particular station over the time series. No value means that samples were not collected.

Year	Station 3	Station 15	Station 16	Station 17	Station 25
1987	1 720	n/a	n/a	n/a	n/a
1988	5 100	11 620	21 740	13 300	n/a
1989	10 900	5 760	19 580	**561 400**	n/a
1990	48 960	**107 720**	7 860	52 220	n/a
1991	5 700	3 140	7 520	6 480	n/a
1992	12 240	62 020	21 360	19 460	n/a
1993	17 960	6 680	27 740	55 480	n/a
1994	14 040	39 168	5 680	21 800	n/a
1995	7 520	8 840	14 920	8 680	n/a
1996	13 440	4 800	7 360	7 120	n/a
1997	15 840	23 760	5 800	12 260	n/a
1998	8 640	12 600	26 280	7 440	n/a
1999	9 080	8 960	9 200	23 520	71 810
2000	45 360	12 560	22 720	13 920	**103 540**
2001	41 040	18 560	10 200	91 008	45 952
2002	31 501	65 892	16 400	23 120	68 782
2003	**95 948**	32 320	21 097	44 800	91 902
2004	30 923	59 245	**37 281**	14 450	65 314

and the next day at Chamcook Harbour (upper Passamaquoddy Bay), 1.55 x 10^6 cells•L^{-1} were observed. On this date, 95% of the sample consisted of *M. rubrum*. Five days later, on September 14, a sample was taken southwest of Station 25 where 4.9 x 10^5 cells•L^{-1} were observed (J.L. Martin, unpublished). The vast inter-annual variability is also evident from Fig. 8. Although Station 25 was only sampled since 1999, it is apparent that there is more consistency in the higher observed concentrations for the longer periods.

The months where the greatest concentrations of *M. rubrum* were observed through the series were June through September and these concentrations occurred during different years for each station (Table 3). Station 3 had the highest concentrations for the sampling period observed most frequently during June, July, and August, whereas Station 15 had maximum concentrations more often from June to September. Station 16 had maximum concentrations observed most frequently in June and July. Stations 17 and 25 had maximum concentrations most frequently in July and August during the same sampling period. However, the higher concentrations for Station 25 occurred in September and October. Table 3 also shows that maximum cell concentrations observed from 1987-2004 were between June and September, with the maximum concentration only occurring in May twice – in 1990 at Station #17 and 1996 at Station #3. The maximum cell density was only observed in October twice as well, in 1990 at Station 16 and 2003 at Station 25. The maximum cell number was never observed in May or October at Station 15; never in May at Station 16; never in June or September at Station 17; and never in May or June at Station 25.

Table 3. Month of the year where the maximum cell concentration of *M. rubrum* occurred at the five stations: #3, #15, #16, #17 and #25. Shaded cells indicate the month and year of the maximum cell density during the sampling period for a particular station. No value indicates that there was no sample collected.

Year	Station 3	Station 15	Station 16	Station 17	Station 25
1987	June				
1988	July	September	July	July	
1989	June	June	September	**August**	
1990	June	**June**	October	May	
1991	July	July	July	July	
1992	August	August	August	August	
1993	August	August	August	August	
1994	June	June	July	August	
1995	September	September	July	August	
1996	May	August	June	August	
1997	June	July	June	July	
1998	August	July	June	July	
1999	July	July	June	July	August
2000	July	July	July	July	**September**
2001	August	September	July	August	August
2002	September	September	September	August	July
2003	**July**	September	September	August	October
2004	August	August	**August**	July	July

As *M. rubrum* was present in samples for 94% of the time, it was not useful to use an unbroken sequence of two or more samples having no occurrence (bloom with two zeroes). Since this would have yielded extremely long average bloom durations of more than 3 yr or 1048 d, various scenarios for defining a "bloom" of *M. rubrum* were therefore explored (Table 4).

Table 4. Determination of a bloom event for *M. rubrum* showing results from each station using criteria such as: bloom duration with two consecutive counts of zero, with one count of zero, using 500 cells•L^{-1} as the baseline and using 1000 cells•L^{-1} as the baseline. Shaded line indicates method used in this paper.

Means	Station 3	Station 15	Station 16	Station 17	Station 25
Duration between two zero counts	632	613	1 961	3 000	2 073
Duration between one zero count	172	178	196	312	644
Duration between counts > 500	38	22	43	31	93
Duration between counts > 1000	**24**	**11**	**30**	**20**	**75**
Duration of annual maximum blooms	58	24	74	54	157

For this paper, it was decided to characterize a bloom event for *M. rubrum* as an event where the baseline for initiation of a bloom was defined as counts greater than 1000 cells•L^{-1} from a particular sample. This made it possible to determine periods when *M. rubrum* was above background levels. Through this scenario, the average bloom period for all stations was 23 d. Other factors used for calculating the duration of the maximum bloom of each year were as follows:

- any bloom duration that extended beyond the calendar year was only counted until December 31st of the current year in order to eliminate overlap for consecutive years;
- blooms lasting all year long were considered to be 365 d in length, ending on December 31st;
- the last date of the study was December 7, 2004. Since occurrences for January of 2005 are not included, that date is considered the end date of any blooms that existed on that date. Therefore, the maximum duration of a bloom in 2004 is 341 d; and
- numbers that were determined by these conditions are noted in the "Length of Bloom" table with ***bold italics*** (Table 6).

In general, 56% of the sample days had greater than 1000 cells•L^{-1} with Station 15 having 45% occurrence over 1000 and Passamaquoddy Bay (Station 25) having 83% occurrence. None of the other stations had occurrences over 1000 more than 60% of the time.

The longest bloom period for the maximum cell density based on greater than 1000 cells•L^{-1} occurred in 2000 at Station 25 and was 203 d (Table 5).

Table 5. Length (in days) of the maximum bloom for each station in each year using the criteria for a bloom of greater than 1000 cells•L^{-1}. No value means that samples were not collected. Shaded areas indicate the year in which the highest concentration was observed during the sampling period.

Year	Station 3	Station 15	Station 16	Station 17	Station 25
1987	7	n/a	n/a	n/a	n/a
1988	21	7	16	35	n/a
1989	49	20	49	**42**	n/a
1990	28	**21**	14	7	n/a
1991	69	1	62	27	n/a
1992	62	7	119	34	n/a
1993	48	41	83	41	n/a
1994	77	63	24	63	n/a
1995	35	14	14	35	n/a
1996	15	1	56	6	n/a
1997	1	7	7	27	n/a
1998	7	7	14	34	n/a
1999	105	1	98	49	132
2000	29	8	63	70	**203**
2001	105	97	42	154	114
2002	175	35	231	91	159
2003	**91**	49	191	126	133
2004	112	28	**181**	84	203

As discussed previously, we consider the baseline for *M. rubrum* to be when the cell concentration is greater than 1000. The duration for the presence that had the maximum cell densities for *M. rubrum* for each station varied from 161-365 d (Table 3, Table 6, Fig. 11). The presence with the maximum concentration and the longest duration (365 d) of the time series occurred in 2000 at Station 25. The presence with the maximum concentration with the next longest length (255 d) occurred at Station 17 in 1989, whereas maximum concentration duration for Stations 3, 15, and 16 were 161 (2003), 218 (1990) and 217 (2004), respectively. Interestingly, Station 25 was the only location where the maximum concentration bloom length and the longest duration occurred in the same year. Therefore, the length of the presence did not necessarily equate to maximum cell density for *M. rubrum* through the sampling period. Stations 3, 17, and 25 also show that since 2000, presence has extended to all or most of the year. Station 16 seems to have the most years (1988, 1997, and 2000) with presence less than 100 d, whereas this did not occur at all at Stations 3, 17 and 25. Note that 1987 and 1988 were not full years of sampling because they were the initial years for these stations.

Table 6. Length (in days) of the presence of *M. rubrum* for each station in each year. No value means that samples were not collected. Shaded areas indicate the year in which the maximum cell density for each station occurred during the sampling period.

Year	Station 3	Station 15	Station 16	Station 17	Station 25
1987	7				
1988	189	126	***83***	***190***	
1989	248	169	***186***	**255**	
1990	196	**218**	***237***	***234***	
1991	311	111	***231***	***267***	
1992	244	139	***365***	197	
1993	209	273	***233***	230	
1994	273	310	***223***	***228***	
1995	183	***258***	***222***	***286***	
1996	182	99	223	***204***	
1997	205	***175***	57	266	
1998	189	***163***	182	***326***	
1999	***241***	***365***	275	***288***	***262***
2000	***365***	***322***	63	***365***	***365***
2001	***365***	224	***181***	***365***	***244***
2002	***365***	***175***	***365***	***365***	***365***
2003	***161***	***365***	***365***	***365***	***365***
2004	***341***	***341***	***217***	***217***	***217***

The date of first occurrence for *M. rubrum* varied considerably between years and stations (Table 7, Fig. 12) and ranged from Day 2 (January 2) to Day 107 (April 17). It tended to occur earlier in the Passamaquoddy Bay Stations (17 and 25) than in the offshore and exposed sites. The mean day of the first occurrence from all sites ranged from 13-35 (January 13-February 4) and the median day ranged from 9-25 (January 9-January 25).

Table 7. Ranges of Julian days for first occurrences of *M. rubrum*, including mean and median days of occurrences for the five stations, 1987-2004.

	Station 3	Station 15	Station 16	Station 17	Station 25
Range for 1st occurrence	2-79	6-107	6-79	2-41	6-23
Mean	35	28	25	19	13
Median	25	20	19	19.5	9

Further information on the description of the occurrences of *M. rubrum* indicates that the median day of the maximum cell abundance ranged from day 200 to day 224 or from July 18–August 12 (Table 8). Median duration of the maximum bloom ranged from 218-314 d, and the median maximum cell abundance ranged from 12 600-70 296 cells•L^{-1}, with Station 25 being 3-fold greater. The mean duration of the presence of *M. rubrum* being greater than 1000 cells•L^{-1} for each station ranged from 11-75 d and had a mean of 23 d, with Station 25 being 3-fold longer. The median day of the first appearance of *M. rubrum* was between January 9 and January 25, early in the year or mid-winter at all locations.

Table 8. Summary of descriptive analyses from data from 1987-2004 on *M. rubrum* including median day of first occurrence, median day of maximum cell abundance, median duration in days of the bloom with the greatest cell abundance, median of the maximum cell abundance for all years, and the mean for the duration of the presence of cells where the count is greater than 1000 cells·L^{-1}.

Variable (units)	Station 3	Station 15	Station 16	Station 17	Station 25
Median day of first appearance (Day of year)	25 Jan 25	20 Jan 20	19 Jan 19	19.5 Jan 19 or 20	9 Jan 9
Median day of maximum cell abundance (Day of year)	200 Jul 18	224 Aug 12	201 Jul 19	216 Aug 4	224 Aug 12
Median maximum bloom duration (days)	225	218	223	266	314
Median annual maximum cell abundance (cells•L^{-1})	13 740	12 600	16 400	19 460	70 296
Mean duration (days) (where count >1000 cells)	23	11	30	20	75

DISCUSSION

Observations in 1931 (Powers 1932), 1967 (McAlice 1968), 1975 (White et al. 1977), and 1977 and 1979 (J.L. Martin, unpublished) indicate that *M. rubrum* is not a new species to the Gulf of Maine or Bay of Fundy and has been known to form brick-red discoloured water in the area. Since the sampling program described here was initiated, red-water sightings as a result of *M. rubrum* have been observed in the Passamaquoddy Bay region in 1989, 1993, 1998, 1999, 2000, 2002, and 2003. Although this suggests that the incidences of red water may be increasing, we do not think this is the case in recent years for two reasons - increased awareness of red tides and water discolouration, and more traffic in the area as a result of salmon aquaculture, tourism, and other activities.

Earlier studies and counts by Gran and Braarud (1935) from 1931 and 1932 indicated that, although *M. rubrum* was observed during their study, it was very scarce. This may have been due to a number of reasons such as: their sampling methods employed the collection of 150-250 cc from Niskin bottles at discrete depths and centrifuging the sample to concentrate the cells; *M. rubrum* tends to be able to swim rapidly and therefore could avoid the sampling bottles; their sampling was conducted at 2-wk intervals so they may have missed the larger blooms; or the years of 1931 and 1932 may not have been high bloom years for *M. rubrum* for the locations they sampled. *M. rubrum* is an extremely delicate organism and cells are easily destroyed. Although these samples were preserved prior to centrifugation, the possibility of cells disintegrating during the process could still have been an issue. Fortunately, past samplings did not employ nets, as *M. rubrum* is extremely fragile and would have been destroyed through contact with the nets.

Even though results from this study were from whole water samples collected by bucket or bottle, we suggest that these numbers are, in reality, an underestimate of the actual numbers in the water at the time, as *M. rubrum* can swim rapidly and appear to avoid sampling devices. Additionally, when profiles of fluorescence were captured in Passamaquoddy Bay through the water column using a CTD, the peak values were most often detected at a depth of 2-3 m during mid-day, showing that often *M. rubrum* was able to maintain higher cell densities below the surface in a thin layer. Samples collected at the depth of 2-3 m supported the assumption that the fluorescence values recorded were associated with the high concentrations of *M. rubrum*. This would have put the major portion of the bloom subsurface, and not at the surface where our samples were collected. Observations at the time indicated that the layers tended to concentrate during times of bright sunlight and low wind.

Prior to the expansion of the aquaculture industry into the Passamaquoddy Bay area, it was perceived that *M. rubrum* blooms and red waters in the area were not toxic and did not cause harm. However, as a result of the high concentrations that have drifted through the net pens in the region, it has been suggested that *M. rubrum* may contribute to stress and mortalities through secondary effects such as asphyxiation due to oxygen depletion (Martin et al. 2001a), or perhaps excess oxygen (R.L. Peterson, Biological Station, 531 Brandy Cove Road, St. Andrews, NB E5B 2L9, pers. commun.). This was also suggested when mass mortalities of marine organisms such as rock lobster, sea urchins, fish, and sharks occurred in South Africa in 1978 (Hortsman 1981).

Numerous attempts over the years to culture *M. rubrum* were unsuccessful (Taylor et al. 1969). In recent years, researchers have been able to culture it, but it can be labour intensive and difficult as it requires feeding *M. rubrum* a food organism, the cryptophyte *Teleaulax* sp., in proper proportions so that the *Teleaulax* sp. does not form dense populations and outcompete the *M. rubrum* (Gustafson et al. 2000; Yih et al. 2004; Myung et al. 2006). It is, therefore, still a difficult organism to study and culture and may be a challenge to grow in mass cultures in order to determine lethality and modes of action through laboratory experiments and exposure to fish.

Results show that the highest concentrations of *M. rubrum* within the study area tend to occur in Passamaquoddy Bay, and this region seems to be more susceptible to *M. rubrum* red tides and therefore a possible threat to salmon farms located in the area. Red-water sightings tend to be common in June and August/September and appear to be linked to periods when water temperatures are at the latter part of the seasonal increase, along with extended periods of sunshine.

Analyses from the study period suggest that the Passamaquoddy Bay region was more conducive to the higher cell densities and blooms of *M. rubrum*. The inshore area has more freshwater influence, little mixing and lower flushing. High numbers coincided with problems which were associated with salmon farms in the Passamaquoddy Bay area in past years (J.L. Martin, unpublished). Results from this study suggest that if concentrations continue to reach high levels, there might be problems with salmon in net pens. Recent years seem to have longer blooms in Passamaquoddy Bay and, should conditions be ideal for *M. rubrum*, these areas will experience higher concentrations and, therefore, farms in this region would be more at risk to *M. rubrum* blooms.

This synthesis provides information on the patterns and trends of populations of *M. rubrum* from 1987-2004 in the southwestern New Brunswick region of the Bay of Fundy area. It is an initial phase of analysis of the data, and the first documentation of the trends for this particular species from the Fundy region. This phytoplankton monitoring program is ongoing, with additional data being collected each year. Continued studies with this valuable long time series and analyses of the phytoplankton data, in association with related physical, chemical and environmental data, will aid our predictive/hindcasting capabilities and improve the search for relationships between the linkages and variables influencing the blooms.

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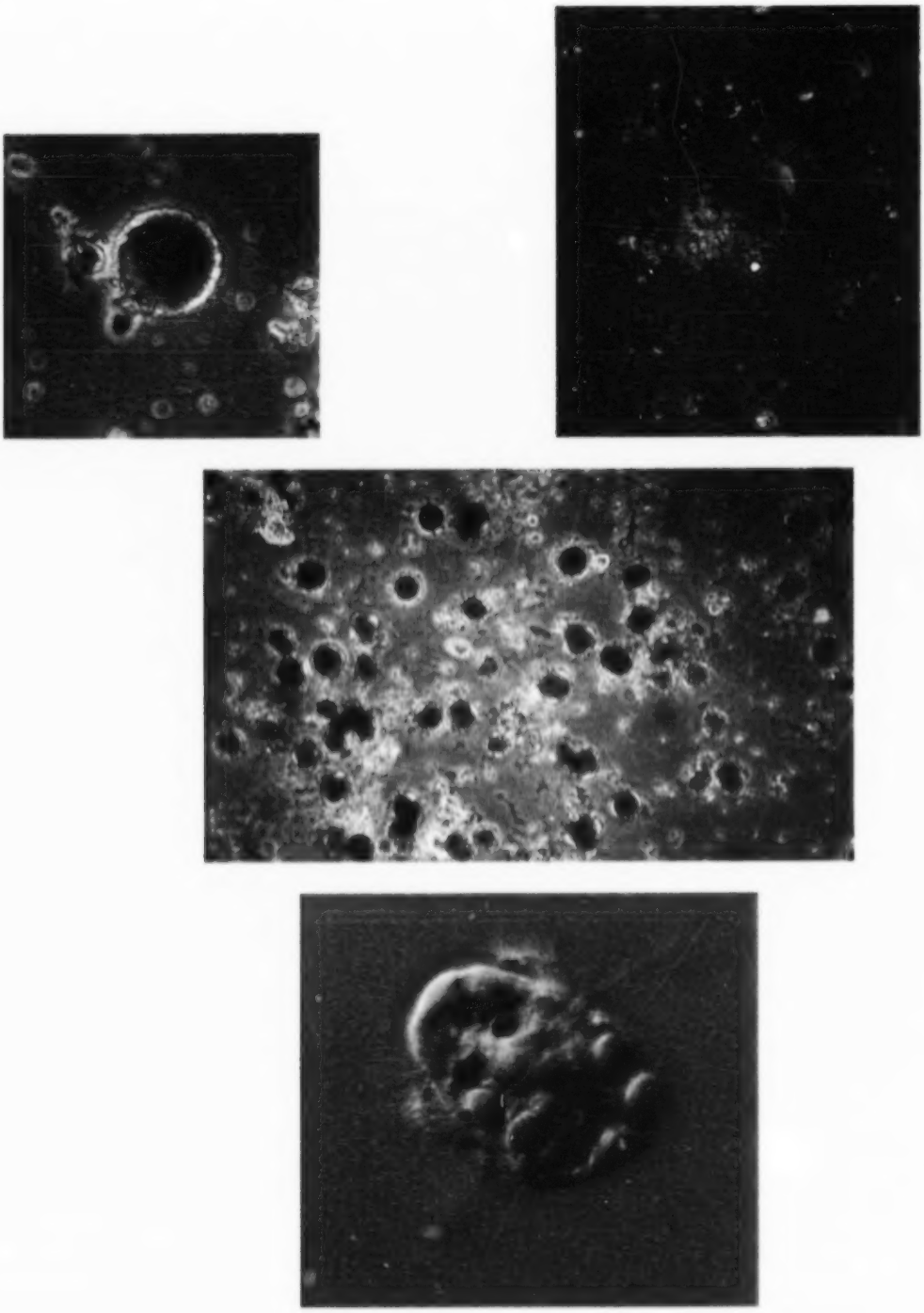

Fig. 1. *M. rubrum* from the Bay of Fundy.

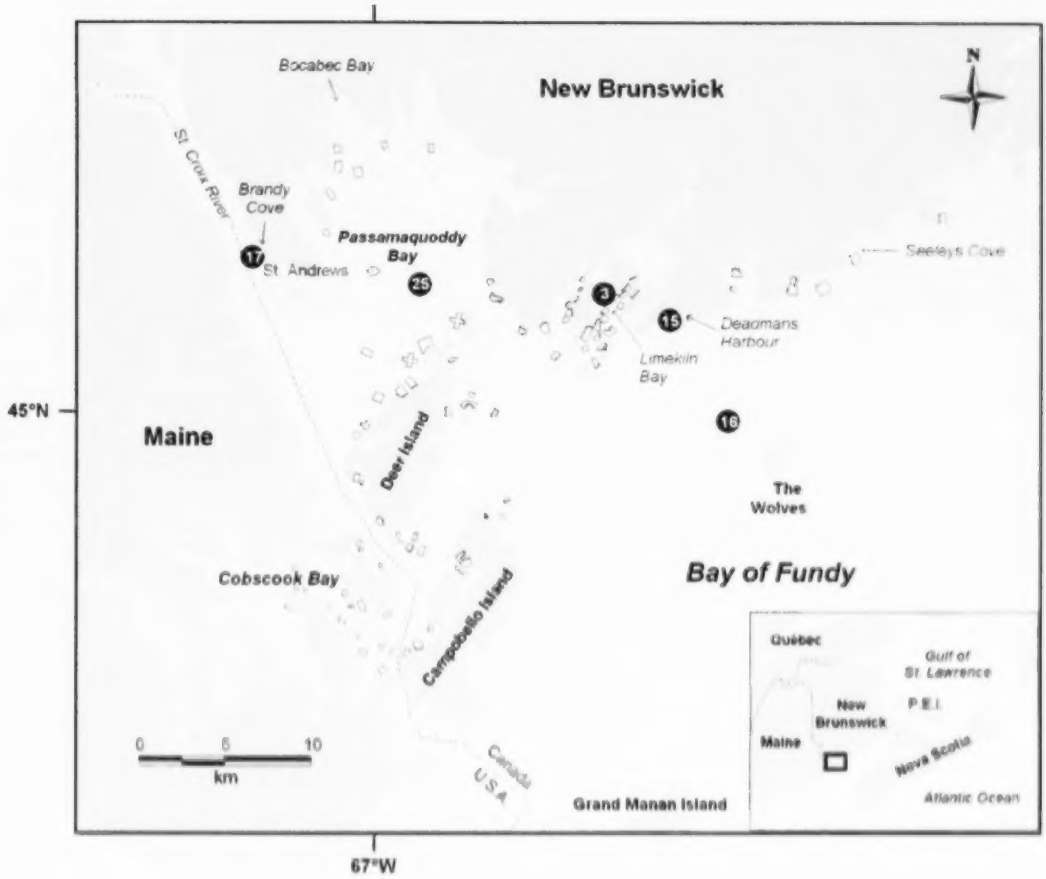

Fig. 2. Map showing sampling stations Brandy Cove (#17), Lime Kiln (#3), Deadmans Harbour (#15), the Wolves Islands (#16) and mid-Passamaquoddy Bay (#25). Salmon farm locations in 2004 are indicated by the outlines shown.

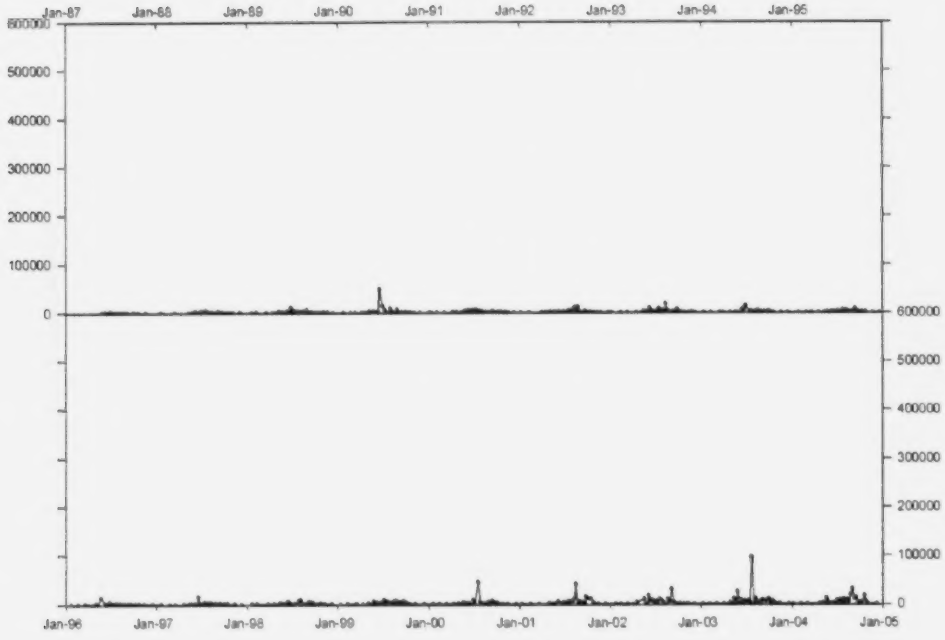

Fig. 3A. Concentrations (cells•L^{-1}) of *M. rubrum* from Lime Kiln Bay (#3) from 1987-2004 on a linear scale. The upper portion of the figure is the 9-yr period 1987-95 and the lower portion is the 9-yr period 1996-2004. The dotted line indicates the 100 000 cells•L^{-1} concentration.

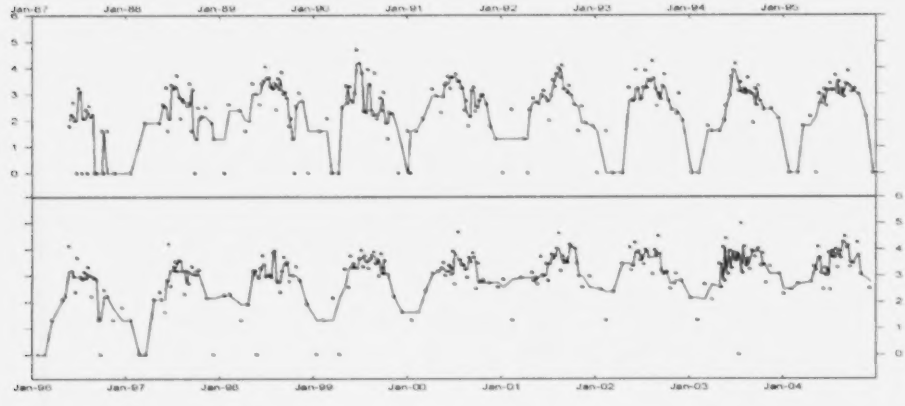

Fig. 3B. Concentrations (cells•L^{-1}) of *M. rubrum* from Lime Kiln Bay (#3) from 1987-2004 on a log-transformed scale. The upper portion of the figure is the 9-yr period 1987-95 and the lower portion is the 9-yr period 1996-2004. The dotted line indicates the 100 000 cells•L^{-1} concentration.

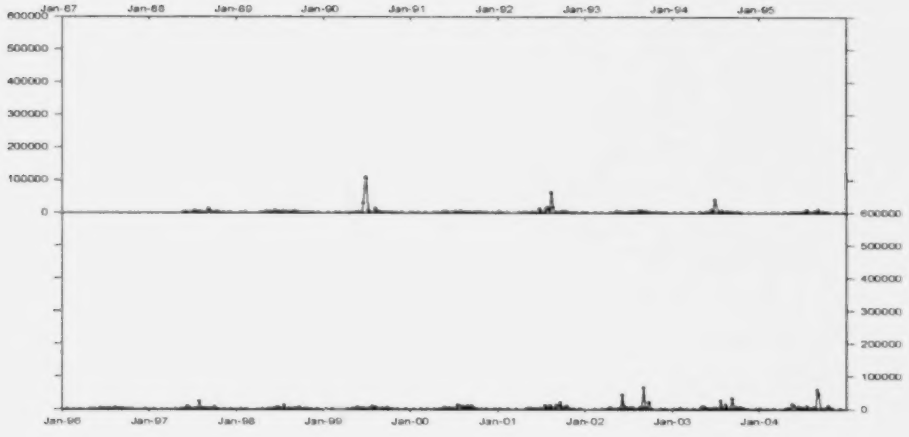

Fig. 4A. Concentrations (cells•L^{-1}) of *M. rubrum* from Deadmans Harbour (#15) from 1988-2004 on a linear scale. The upper portion of figure is the 8-yr period 1988-95 and the lower portion is the 9-yr period 1996-2004. The dotted line indicates the 100 000 cells•L^{-1} concentration.

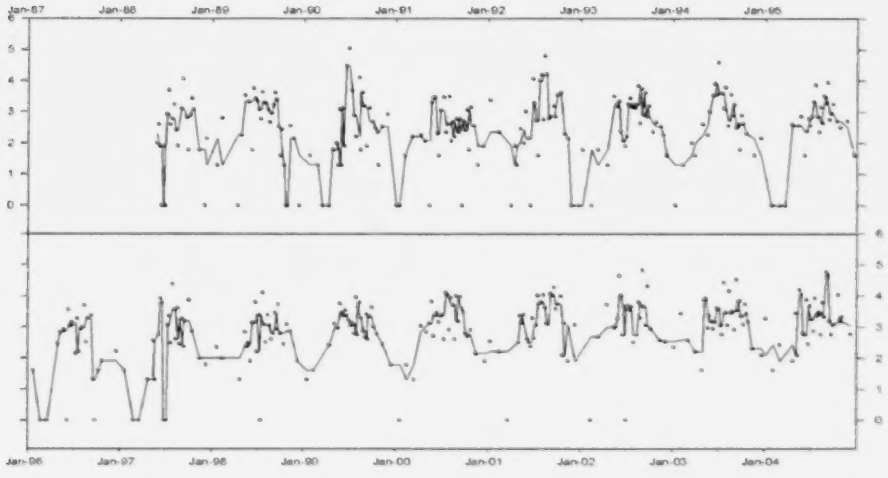

Fig. 4B. Concentrations (cells•L^{-1}) of *M. rubrum* from Deadmans Harbour (#15) from 1988-2004 on a log-transformed scale. The upper portion of the figure is the 8-yr 1988-95 and the lower portion is the 9-yr 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

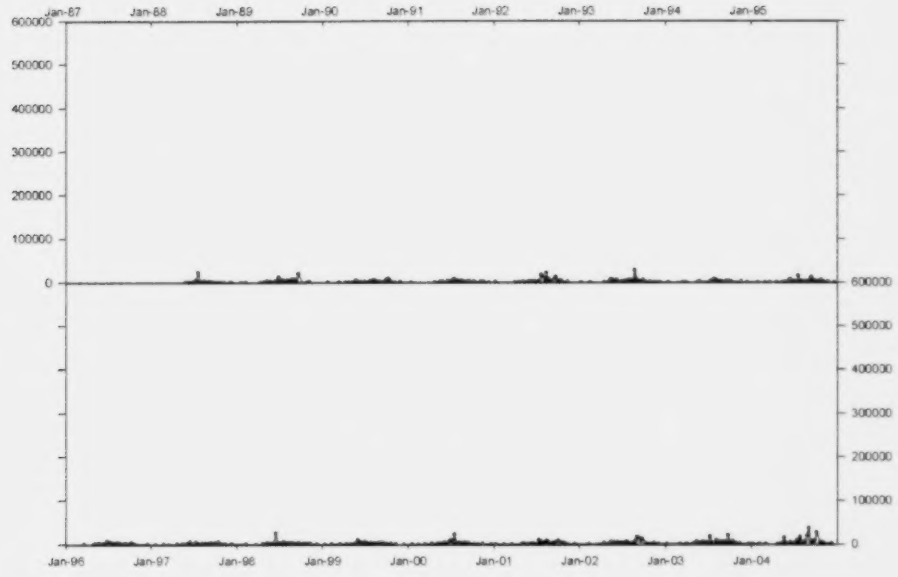

Fig. 5A. Concentrations (cells•L^{-1}) of *M. rubrum* from the Wolves Islands (#16) from 1988-2004 on a linear scale. The upper portion of the figure is the 8-yr period 1988-95 and the lower portion is the 9-yr period 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

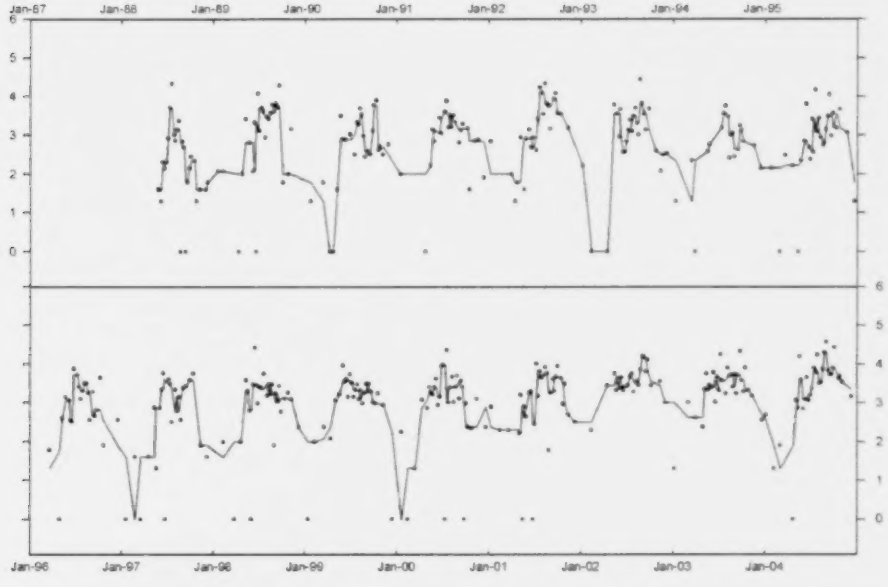

Fig. 5B. Concentrations (cells•L^{-1}) of *M. rubrum* from Wolves (#16) from 1988-2004 on a log-transformed scale. The upper portion of figure is the 8-yr period 1988-95 and the lower portion is the 9-yr period 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

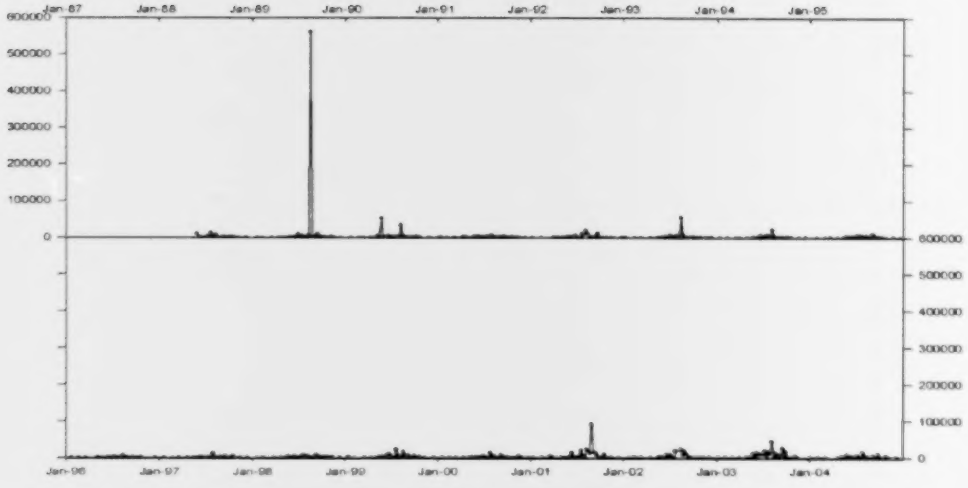

Fig. 6A. Concentrations (cells•L^{-1}) of *M. rubrum* from Brandy Cove (#17) from 1988-2004 on a linear scale. The upper portion of figure is the 8-yr 1988-95 and the lower portion is the 9-yr 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

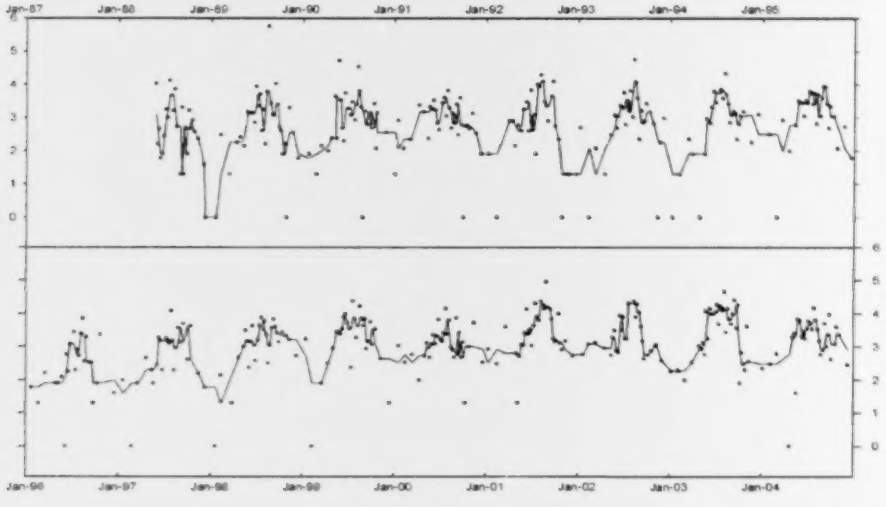

Fig. 6B. Concentrations (cells•L^{-1}) of *M. rubrum* from Brandy Cove (#17) from 1988-2004 on a log-transformed scale. The upper portion of the figure is the 8-yr 1988-95 and the lower portion is the 9-yr 1996-2004. Dotted line indicates the 100 000 cells•L^{-1} concentration.

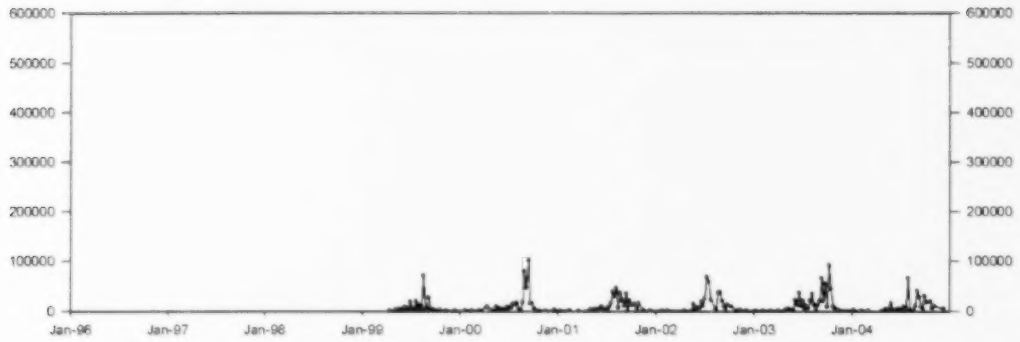

Fig. 7A. Concentrations (cells•L^{-1}) of *M. rubrum* from mid-Passamaquoddy Bay (#25) on a linear scale (1999-2004). Dotted line indicates the 100 000 cells•L^{-1} concentration.

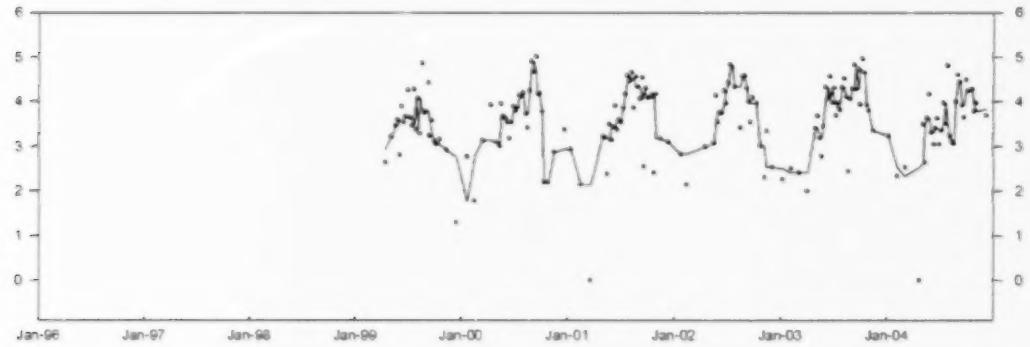

Fig. 7B. Concentrations (cells•L^{-1}) of M. rubrum from mid-Passamaquoddy Bay (#25) on a log-transformed scale (1999-2004). Dotted line indicates the 100 000 cells•L^{-1} concentration.

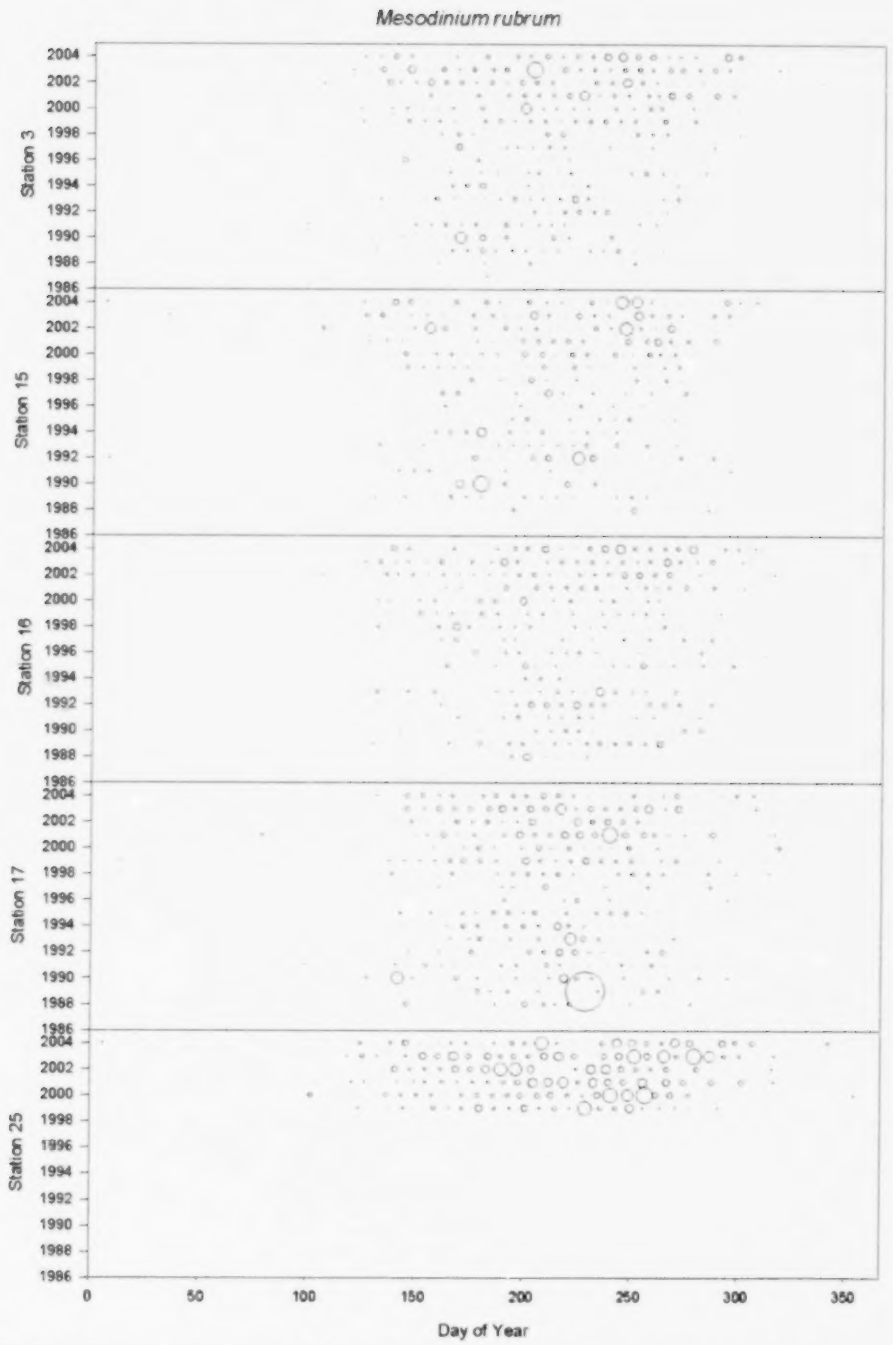

Fig. 8. Bubble plots showing the *M. rubrum* presence from 1987-2004. The concentration of *M. rubrum* is proportional to the area of the circle. Station 25 was not sampled prior to 1999.

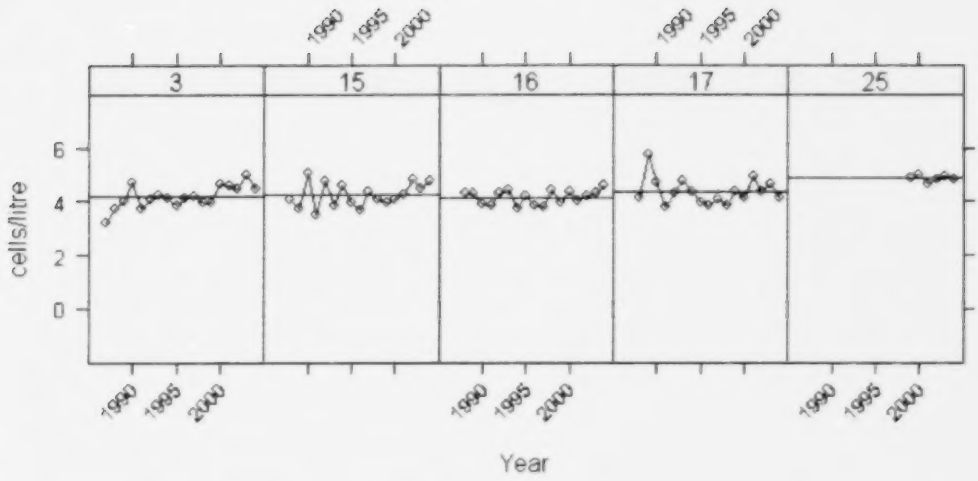

Fig. 9. Maximum density (cells•L^{-1}) of *M. rubrum* at Stations 3, 15, 16, 17, and 25 on a log-transformed scale. Solid line indicates the mean of the log cell concentrations.

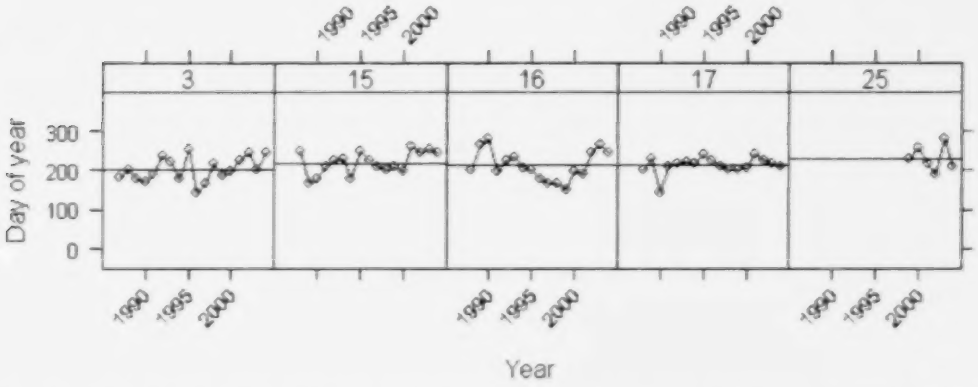

Fig. 10. Day of the year that the maximum cell density was observed. Solid line indicates the mean.

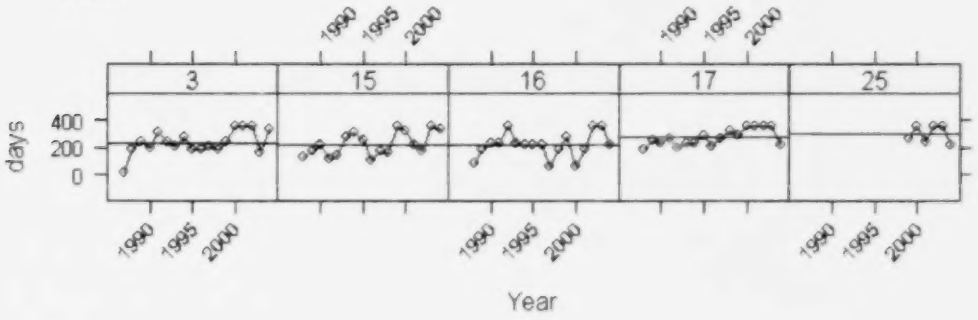

Fig. 11. Length of the bloom containing the maximum cell density for each year 1987-2004.

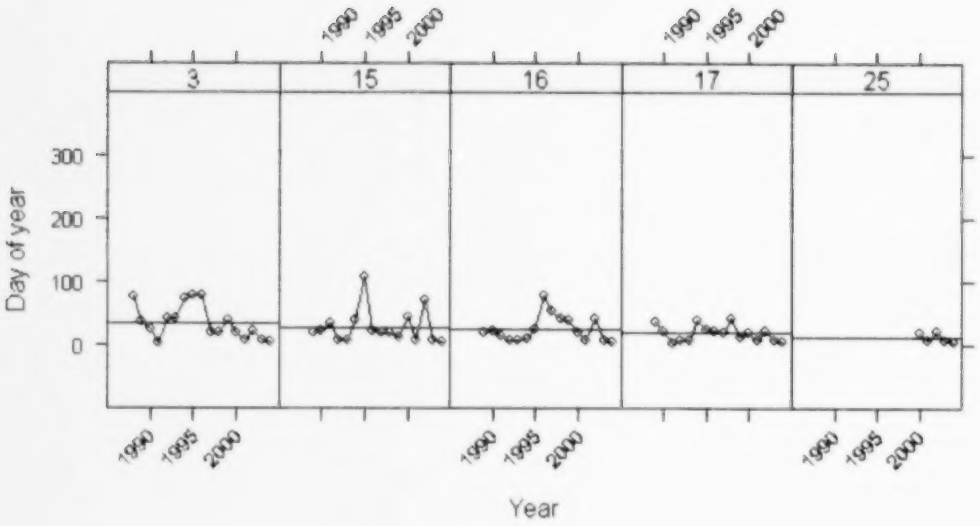

Fig. 12. Date of the first appearance of *M. rubrum* cells in a given year.